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Oxidant Air Pollution Impact to the Forests of Eastern United States

A Literature Review

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16. ABSTRACT

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Potential threats to eastern forest tree species are reviewed through a comparison of various fumigation studies in laboratory and field situations. The concept of hidden injury is discussed as being a possible major impact problem facing analysis of real losses.

The authors present evidence that would suggest that many forest tree species indigenous to the Eastern United States may already be detrimentally impacted by previous high oxidant episodes. They further suggest that even more drastic and only long term reversible effects to the forest ecosystem will follow a trend of increasing oxidant air pollution in many major forested regions of this area of the United States

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OXIDANT AIR POLLUTION IMPACT TO THE FORESTS OF EASTERN UNITED STATES - A LITERATURE REVIEW

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FOREWORD

Effective regulatory and enforcement actions by the Environmental Protection Agency would be virtually impossible without sound scientific data on pollutants and their impact on environmental stability and human health. Responsibility for building this data base has been assigned to EPA's Office of Research and Development and its 15 major field installations, one of which is the Corvallis Environmental Research Laboratory (CERL).

The primary mission of the Corvallis Laboratory is research on the effects of environmental pollutants on terrestrial, freshwater, and marine ecosystems; the behavior, effects and control of pollutants in lake systems; and the development of predictive models on the movement of pollutants in the biosphere.

The forests of the eastern United States are a valuable natural resource providing timber production, recreation, wildlife habitat and watersheds. This resource is increasingly threatened by photochemical oxidants which are transported great distances in phytotoxic concentrations from populated areas to the rural forest environment. This report attempts to describe the real and potential impacts of photochemical oxidants on eastern forest ecosystems. Information of this kind is necessary to assure full assessment of the cost/benefits of EPA's air pollution control strategies as well as input for the Prevention of Significant Deterioration legislation.

Thomas A. Murphy
Director, CERL

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INTRODUCTION

Air pollution has been recognized as a threat to forest productivity for more than one hundred years (Stoeckhardt, 1871). It was generally assumed that the importance of air pollution was restricted to the immediate vicinity of industrial complexes. Impacts, therefore, were considered to be local in nature. The pre-1950 air pollution research dealt primarily with the effects of industrial stack gases and fumes (primarily SO_2) on crops and woodlands. Several reviews that summarize the literature dealing with the effects of industrial emissions on forests are available (Scurfield, 1960; Hepting, 1964, 1966, 1968; Keller, 1968; Knabe, 1971).

More recently a new threat to forest productivity has been recognized. Increased levels of air pollution have resulted from increased use of automobiles and demands for electrical power since the 1940's (Table 1) (Nicholson, 1977). In the early 1950's several researchers determined that photochemical oxidant air pollution was causing damage to a number of plant species in the Los Angeles Basin (Middleton et al., 1950; Haagen-Smit et al., 1952). Damage to eastern white pine (Berry, 1961; Berry and Ripperton, 1963) and ponderosa pine (Miller, 1973) was shown to be caused by O_3, the major component of photochemical oxidant air pollution. Since that time, interest concerning the impacts of photochemical oxidants on forests has increased.

It is now known that air pollution problems are not restricted to metropolitan environments. Even relatively remote mountainous areas of the east are adversely affected (Hayes and Skelly, 1977). The potential for damage to forests is great. The land areas affected probably include the entire United States east of the Mississippi River. Far too little is known of the photochemical oxidant impact on eastern forests to make reliable estimates of dollar losses.

The impact may go far beyond mere dollar value reductions. Irreversible changes in the structure and function of forest ecosystems that go unnoticed at the present may have profound effects on our way of life in the future. There is presently an urgent need to study the effects of photochemical oxidants on the eastern forests before deleterious changes take place. The post mortem approach to research (Treshow, 1968) may prove to be inadequate in protecting our forest resources.

The purpose of the present report is to provide a summary of the available literature that is pertinent to a study of photochemical oxidant air pollution effects to the forests of eastern United States. Sections dealing with the gases involved in plant damage, the etiology of the diseases of white pine that are caused by oxidant air pollution, and the known effects of the photochemical oxidants on forest vegetation are included.

TABLE 1. CHRONOLOGICAL LISTING OF FOUR PARAMETERS RELATED TO AIR POLLUTION EMISSIONS FOR THE PERIOD 1900 to 1970 IN THE U.S. AND VIRGINIA

	Population in 1,000's[a]		Value Added to Manufactured Goods In Millions of Dollars[b,g]		Product of Electric Power Using Fuels by Public Utilities in 1,000,000 KWH[c]			Motor Vehicle Registrations In 1,000's[d]	
Year	U.S.	VA	U.S.	VA	U.S.	VA	Year	U.S.	VA
1975	212,000	5,032	405,225 (1973)[e]	6,197.0 (1972)[e]	1,512,603	34,078	1975	133,727	3,172
70	204,879	4,648	300,228	4,921.5	1,282,254	27,838	1970	108,407	2,577
65	194,303	N/A	226,940	3,573.6	851,341	22,577	1965	90,358	2,039
60	180,671	3,964	153,999	2,433.0	603.342	17,068	1960	73,869	1,534
55	165,275	N/A	135,023	1,827.0	433,678	8,493	1955	62,689	1,327
50	151,684	3,319	89,750	1,326.5	233,115	5,536	1950	49,162	984
45	139,928	N/A	N/A	1,051.6 (1947)[e]	142,431	3.056	1945	31,035	607
40	132,122	2,678	24,487	376.3 (1939)[e]	94,700	1,724	1941	34,894	583
35	127,250	N/A	18,553	247.0[f]	56,915	N/A	1931-1940	278,294	4,257
30	123,077	2,422	18,601	366.4[f]	59,922	N/A	1921-1930	119,199	3,003
25	115,829	N/A	25,668	274.8[f]	39,653	N/A	1911-1920	38,809	434
20	106,461	2,309	23,842	228.2[f]	23,644	N/A	1906-1910	1,230	7
15	100,546	N/A	9,286	108.7 (1914)[e]	N/A	N/A			
10	92,407	2,062	8,160	94.2 (1909)[e]	N/A	N/A			
05	83,822	N/A	6,019	65.2 (1904)[e]	N/A	N/A			
1900	76,094	1,854	4,647	49.3	N/A	N/A			

[a] References: U.S.: 1975 (85), 1900-1970 (83); Virginia: 1975 (12), 1900-1970 (83).

[b] References: U.S.: 1973 (85), 1900-1970 (83); Virginia: 1972 (84), 1900-1970 (50).

[c] Data was compiled from the monthy publication of the U.S. Federal Power Commission entitled: Production of Electrical Energy in the U.S.

[d] References: U.S.: 1975 (85), 1906-1970 (83); Data for Virginia was compiled from the annual/bionnial reports of the Commissioner of the Division of Motor Vehicles, Commonwealth of Virginia for the years 1955-1975.

[e] Where data was not available for a given year, the most recent data is presented as shown.

[f] Where actual data was not available for a given year, data presented represents an average of the previous and subsequent years.

[g] Value added by manufacturer: This figure is derived by subtracting the cost of the materials, supplies, fuel, purchased electricity, and contract work from the value of shipments for products manufactured plus receipts for services rendered. The result of this calculation is then adjusted by the addition of value added by merchandising operations (the difference between the sales value and cost of merchandise sold without further manufacture processing or assembly) plus the net charge in finished goods and work-in-process inventories between the beginning and end of the year (50).

CONCLUSIONS

Photochemical oxidant air pollution presents a formidable threat to the continued productivity of the forests in the eastern United States. Sensitive species have been identified. Little is known about the factors that affect plant sensitivity in the forest and preliminary greenhouse fumigation studies have shown that O_3 may reduce the growth of seedlings. Knowledge of the growth impact on mature trees is lacking. Potential photochemical oxidant impacts on the population and plant community level have been discussed, but field data are lacking.

In general, very little is known of the actual impact of photochemical oxidant air pollution on the forests of the eastern United States. Data are needed that will identify and quantify actual impacts in the forest. Of critical concern are the effects of photochemical oxidants on forest productivity. Specific areas of needed research include:

1) Determination of background pollutant levels so that adequate and realistic air quality standards can be established.

2) Continued dose-response studies that are designed to measure plant responses to pollutants as they occur in the ambient air.

3) Determination of the actual impact of photochemical oxidants on tree growth in the forest.

4) Continued breeding of important tree species for pollutant tolerance.

5) Continued study on the feasibility of establishing bioindicator systems that will allow for estimation of growth impacts.

6) Development of techniques that will identify changes in plant communities and allow for prediction of the effects of any measured change.

The only real solution to pollution is abatement. The prospects for abatement of photochemical oxidant air pollution are remote, at best.

PHOTOCHEMICAL OXIDANT AIR POLLUTION IN THE EASTERN UNITED STATES

THE PHOTOCHEMICAL OXIDANTS

The photochemical oxidants include ozone (O_3), the peroxyacyl nitrates, of which peroxyacetyl nitrate (PAN) is the most important, and the nitrogen oxides (NO, NO_2, NO_x). These compounds occur in polluted air as a result of photochemical reactions involving primary pollutants or direct emissions. The sources of photochemical oxidants (Wood, 1968) and their reactions (Stephens, 1969) have been discussed.

Ozone is the most widespread and important photochemical oxidant (Heggestad, 1969). The oxides of nitrogen and peroxyacyl nitrates are rarely found in the ambient air of the eastern United States and are therefore considered to be of little importance. There are, however, reports that implicate the nitrogen oxides (Skelly et al., 1972) and peroxyacyl nitrates (Pearson et al., 1974) as phytotoxicants in the eastern United States.

Ozone occurs through natural processes involving transport from the stratosphere, lightning, or photochemical generation from natural precursors (Rasmussen and Went, 1965) or through photochemical generation from precursors of anthropogenic origin (primary pollutants). Photochemical generation from anthropogenic precursors are thought to be the most important source of O_3.

The nitrogen oxides occur primarily through processes that involve high temperature combusion of fossil fuels such as internal combustion engines or stationary fossil fuel consuming power plants. Other sources include the manufacture of nitric acid, nitrated propellants, nitrogen fertilizer and nylon intermediates (Wood, 1968).

The peroxyacyl nitrates are formed almost exclusively from the photochemical reaction of unsaturated hydrocarbons with oxides of nitrogen.

There are natural sources of precursors for each of the above mentioned pollutants. Nitrogen oxides (Robinson and Robbins, 1970) and hydrocarbons capable of photochemical reactions resulting in O_3 (Rasmussen and Went, 1965) and PAN (Stephens and Scott, 1962) are known. For purposes of setting air pollution standards, reliable estimates of the natural background concentrations of the photochemical oxidants are needed but to date, such estimates are not available.

INCIDENCE OF OZONE IN THE AIR OF THE EASTERN UNITED STATES

During the 1950's air pollution was generally considered to be a problem of large metropolitan areas or industrial sources. However, interest in air pollution in rural areas increased after the discovery that atmospheric oxi-

dants were found to be the cause of several plant disorders whose etiology was previously unknown. Richards et al. (1958) and Heggestad and Middleton (1959) demonstrated the causal relationships between oxidants and grape stipple and tobacco weather fleck, respectively. Monitoring studies were conducted at several rural areas in the U.S. and Canada beginning in the early 1960's.

Leone et al. (1962) measured oxidant (reported as O_3) concentrations during September and October, 1960 at three rural sites in New Jersey. Oxidant concentrations occurred during periods of high barometric pressure and the site nearest a large industrial-urban complex had the highest pollution levels.

In a similar study, Cole and Katz (1966) measured oxidant concentrations near Lake Erie in southern Ontario during the summer of 1960 and 1961. The highest maximum oxidant concentrations were above 10 pphm during both years. The occurrence of oxidant concentrations high enough to cause flecking of tobacco leaves was associated with the presence of high pressure systems.

During 1966 and 1967 Costonis and Sinclair (1969a,b) measured oxidant concentrations at rural sites in central New York. The highest 4 hr mean oxidant concentration was 5.2 and 8.5 pphm in 1966 and 1967, respectively.

Oxidant concentrations were measured from June 6 - July 6 at a rural site in Pocohantas County, West Virginia in 1961 (Berry and Ripperton, 1963) and near Asheville, North Carolina in 1962 (Berry, 1964a). The highest sustained oxidant concentrations in West Virginia and North Carolina were 6.5 and 4.2 pphm, respectively. In a later study Costonis (1971) measured oxidant concentrations in the Pisgah National Forest in western North Carolina during the summer of 1969. He recorded a maximum sustained oxidant concentration of 4 pphm.

The studies that were conducted in urbanized regions recorded higher maximum oxidant concentrations than those in the relatively remote mountainous areas of West Virginia and North Carolina. The low oxidant concentrations measured at remote West Virginia and North Carolina sites may have represented the natural background levels of oxidants at that time.

Recent studies have demonstrated the impact of urban pollution on downwind sites. Cleveland and Kleiner (1975) showed that rural areas downwind of the Philadelphia-Camden urban complex often had higher O_3 concentrations than the city. Ozone concentrations often exceeded the national ambient air quality standard (NAAQS) at rural and urban sites. Cleveland et al. (1976) showed that O_3 concentrations in Connecticut and Massachusetts were highest when the wind came from the New York City area, and were often higher than the O_3 concentration in New York City. These studies demonstrated the transport of O_3 and/or its precursors from urban sources to rural, downwind areas.

Stasiuk and Coffey (1974) and Coffey and Stasiuk (1975) point out that O_3 concentrations at rural and urban sites reach maximal values on the same days. This implies a common source of either O_3 or its precursors. Therefore, the cities could not be responsible for the high ozone concentrations measured

simultaneously throughout the state. They suggest that O_3 or its precursors result from natural phenomena such as photochemical generation from natural precursors or transport from the stratosphere.

Several investigators have shown that sites remote from urban centers often experience O_3 concentrations above the NAAQS. Hayes and Skelly (1977) correlated high oxidant (above the NAAQS, 8 pphm for 1 hr) concentrations in the mountains of western Virginia with winds from the north and northeast. They concluded that O_3 or its precursors were transported from the urban northeast corridor and Lake States into Virginia where they became entrapped within a stagnant high pressure system. Their interpretation of the results of the 1975 episode was supported by Husar et al. (1977). The maximum oxidant concentrations in the mountains of western Virginia were above 15 pphm during 1976 and 1977 (Skelly, 1977). Oxidant concentrations during July, 1977 in western Virginia were above the NAAQS 30 percent of the time (Skelly and Johnston, 1978). They used 4 pollution monitoring sites established throughout the Blue Ridge and Southern Appalachian Mountains of Virginia. During 1977 they reported several oxidant pollution episodes with respect to intensity, duration and impact to the forest vetatation in the area. During May, 218 hr above the NAAQS were recorded with the episode extending from May 12-20. During July 14-24 a similar episode with a peak of 16.6 pphm O_3 was recorded and the NAAQS was exceeded at least 30% of the actual time at all 4 sites. They suggested that there was strong meterological evidence that the system that originated the episode had traveled from the midwest portion of the United States. Galloway and Skelly (1978)published a report that demonstrated that sulfates also increased during this same peak episode period. Severe restrictions in visibility were also noted.

Wolff et al. (1977) found that the movement of O_3 concentrations above the NAAQS into new areas coincided with the movement of high pressure systems. They suggested a process involving long distance transport of O_3 or its precursors as the mechanism responsible for the occurrence of high O_3 concentrations at sites from urban sources.

Vukovich et al. (1977) associated high O_3 concentrations in the eastern U.S. with slow moving high pressure systems. The highest O_3 concentrations within these systems were found on the back side of the high pressure system, corresponding with the air parcel that would be expected to have the longest residence time within the system. It was suggested that the high O_3 concentrations in the eastern United States were due to the injection of O_3 precursors into the system and the long residence time allowed for the accumulation of O_3. The precursors were thought to be of anthropogenic origin.

In general, the O_3 measured at rural sites may result from local sources if urban areas are close, from a few miles away in an urban plume or from several hundred miles away by long range transport in a slow moving high pressure system.

Comparison of the early oxidant measurements of Berry and Ripperton (1963), Berry (1964a), and Costonis (1971) with the more recent measurements of Hayes and Skelly (1977), Skelly et al. (1977), Skelly (1977), and Skelly

and Johnston (1978) may indicate a dramatic increase in oxidant concentrations at rural sites remote from urban areas. Recently reported oxidant levels have been two to three times higher in the 1975-1977 period than those reported by Berry and Ripperton (1963) at similar sites in the southern Appalachians. The trend of increasing oxidant air pollution, if it continues, will present an increasing challenge to the productivity of the forest resources of the east. Wood (1968) predicted that photochemical air pollutants will continue to be of major concern beyond the year 2000.

DISEASES OF EASTERN WHITE PINE CAUSED BY OZONE

NEEDLE BLIGHT OF EASTERN WHITE PINE

The determination that needle blight of eastern white pine was caused by exposure to O_3 was provided by several interesting etiological studies. More than fifty years passed from the first report of the disease symptoms until proof of cause and effects was established. The fact that symptoms of needle blight were present around the turn of the century (Dana, 1908) indicate that air pollution problems are not new. A complete review of this topic has been prepared by Gerhold (1977) and more recently by Nicholson (1977). Table 2 presents a review of the past white pine studies (Nicholson, 1977).

The diseases of eastern white pine (Pinus strobus L.) called needle blight, white pine blight, semimature-tissue needle blight (SNB), tipburn, emergence tipburn, post-emergence chronic tipburn, post-emergence acute tipburn, and others were puzzling to forest pathologists for years. Needle blight of eastern white pine was first described by Dana (1908) in New Hampshire. Other early reports of its occurrence include Spaulding (1909) in New York and New England and Faull (1922) in southern Ontario. Later reports included large areas of the southeastern United States (Toole, 1949) and Maryland (Walker, 1946). The disease has been reported throughout the range of eastern white pine.

The symptoms of needle blight were described as a reddening of the needle tips followed by a progressive dieback (Dana, 1908; Spaulding, 1909; Faull, 1922; Gussow, 1928; Spaulding and Hansbrough, 1943; Walker, 1946; Baldwin, 1954). The symptomatic trees were scattered randomly within white pine stands.

The investigators attributed needle blight to a number of possible causes. Faull (1922) reported that needle blight was worse on trees of greater than 6 inch diameter. The feeder roots of unhealthy trees were often dead and the disease was not transmitted by fusion of healthy and blighted branches. Drought was believed to play a role in the disease. Gussow (1928), however, suggested that excess water was the cause. Hudson (1944) demonstrated that excess water killed the mycorrhizae. This resulted in reduced root vigor and tipburn from drought stress. Deuber (1931) also suggested drought as the cause of needle blight. Swingle (1944) discounted the role of water stress, either in excess or drought, because diseased trees were found among the healthy trees.

Toole (1949) found that several fungicides had no effect on the needle blight disease. He suggested that the causal agent was a root aphid or a virus. However, the lack of graft transmission reported by Faull (1922) seemed to discount the possibility of viral infection.

TABLE 2. A COMPARISON OF VARIOUS WHITE PINE NEEDLE BLIGHTS ACCORDING TO HEPTING/BERRY, LINZON, COSTONIS, AND DOCHINGER[a]

Researcher	Hepting/Berry						Linzon		Costonis	Dochinger
Study Area	West Virginia, Tennessee, North Carolina						Ontario, Canada		New York	Ohio
Diagnostic Terminology	Bifusella Blight	Brown Spot	Emergence Tipburn	Post Emergence Chronic Tipburn	Post Emergence acute Tipburn	Semimature Needle	Ozone Damage	Sulfur Dioxide	Needle Blight	Chlorotic Dwarf
Needles Affected	Current	Current	Current	Any Usually Current	Any	Current	Current	Any	Current	Current
Time of Obvious Blighting	In Spring on 1 Yr. old Needles	In Spring on 1 yr. old Needles	In Summer when newly Emerging	Any Season	Any Season	Late June to Mid-August	Summer	Any Season	Early Summer	Early Summer
Margin: Healthy vs. Diseased Tissue	Sharp	Sharp	Sharp	Indefinite	Usually Sharp	Sharp	Sharp	Usually Sharp	Sharp	Gradual
Fungal Fruiting Bodies	Large Black	Small Black	None	None	None	None	None	None	None	None
Mottling	None	Discrete Spotting	None	Common	None	Common	None	Very Slight Only in Chronic Exposures	Common	Common
Needle Shedding	Sometimes in 1 yr. old needles	Profuse in Spring	None	Profuse in 2nd yr. needles	Sometimes	Profuse in 2nd yr. needles	Not discussed	Profuse in 2nd yr. needles	Profuse in 2nd yr. needles	Profuse in 2nd yr. needles
Onset	Sudden	Gradual	Sudden	Gradual	Sudden	Sudden	Sudden	Sudden	Sudden	Sudden
Color of Lesions	Black Stromata	Chlorotic Processing to Brown	Reddish-Brown to Brown to Grayish	Reddish-Brown to Brown to Grayish	Brown Necrosis	Pink Changing to Orange-Red	Pale Green to Bronze to Orange-Brown	Gray Green to White to Reddish-Brown	Silver to Yellow-Pink to Yellow-Brown	Yellow
Cause	Bifusella Linearis	Scirbhia Acocola	O_3	Unknown Probably O_3 and SO_2	SO_2 and chlorine	Probably O_3 and SO_2	O_3	SO_2	O_3 and/or SO_2	O_3 and SO_2
Remarks	Usually Strikes Single Trees	Resin Drop Usually Found on Lesion	Widespread Problem In Eastern U.S.	Gen. Chlorosis Then Emerg. Tipburn	Assoc. with Indus. Areas in TN	Cause Never Proven to be O_3 and SO_2	O_3 Conc. Used where 60 pphm for 2 H	Assoc. with Point Sources	After 72 H. O_3/SO_2 damage was the same	Trees reach 2'-4' tall maximum
References	35	35, 67	4, 35	6, 34	6, 34	15, 47, 49	47, 49	43, 47, 49	13, 14, 15	21, 25

[a] Chart format taken from Hepting and Berry (35).

Following a review of the literature and the results of a survey of needle blighted trees in New Hampshire, Baldwin (1954) observed that a small proportion of the trees was affected and eastern white pine was the only species exhibiting symptoms. The injured trees were randomly scattered within stands in many soil and moisture conditions. He concluded that needle blight was associated with drought from the previous year.

Linzon (1960) made a detailed description of the progression of needle blight symptoms. He found that the dieback did not begin at the needle tips, as previously reported. Rather, the first symptoms were faint, pinkish spots on the stomata-bearing surfaces of the semimature tissue of elongating needles. The spots became orange-red and then spread toward the needle tip. New injury from subsequent disease attacks first appeared in the semimature tissue and spread distally. He concluded that the disease was related to unfavorable environmental conditions and was genetically controlled.

Grafting studies further supported the contention that the disease was not communicable (Berry, 1961; Linzon, 1969; Berry and Hepting, 1964). In each experiment the four combinations of healthy and diseased scion and stock were tested. Diseased scion remained diseased and healthy scion remained healthy, regardless of root stock. It was concluded that the disease was genetically controlled.

Studies of diseased trees transplanted from areas of high disease incidence to areas of low disease incidence further indicated the abiotic nature of the disease, and implicated atmospheric constituents as the probable cause (Berry, 1961). Symptomatic trees moved from an area of high disease incidence (Marlington, West Virginia) to an area of low disease incidence (North Carolina) exhibited no symptoms of disease in the second year after transplanting. Symptomatic trees dug up and put back in the same hole, or moved 20 miles to another location remained symptomatic.

Ozone was shown to be the causal agent of needle blight when Berry (1961) induced symptoms on sensitive trees by fumigating them with 10 pphm O_3 for 2 hr. The symptoms were identical to those seen on sensitive trees injured in ambient air. Trees that were not sensitive outdoors were not injured in the artificial fumigations.

The fact that O_3 caused emergence tipburn (or needle blight) was confirmed in the studies reported by Berry and Ripperton (1963). Sensitive ramets from a single parent enclosed in chambers supplied with air from which O_3 was removed (MnO_4 and activated charcoal filters) were protected from injury. Sensitive ramets from the same parent grown in ambient air were injured. Fumigations using O_3 doses similar to those measured in the field caused injury symptoms identical to those observed in the field.

That O_3 was the causal agent of emergence tipburn was further substantiated by Costonis and Sinclair (1969a,b). High ambient oxidant levels preceded the appearance of symptoms by one or two days. Needle retention on sensitive trees was greater on branches that were bagged and supplied with filtered air than on branches that were not bagged. Interaction of ozone and two fungi, Lophodermium pinastri and Aureobasidium pullulans were not found (Costonis and Sinclair, 1972).

CHLOROTIC DWARF DISEASE

Another puzzling problem for forest pathologists was the chlorotic dwarf disease of eastern white pine. Swingle (1944) described the symptoms as stunted roots, greenish-yellow to yellow stunted tips and premature needle drop. He recognized the similarities between the chlorotic dwarf and needle blight diseases of eastern white pine.

The grafting experiments of Dochinger and Seliskar (1965) demonstrated that the chlorotic dwarf disease was a genetically controlled trait. Dochinger and co-workers demonstrated that the chlorotic dwarf disease was caused by an interaction of O_3 and SO_2 (Dochinger 1964, 1968; Dochinger and Heck, 1969; Dochinger and Seliskar, 1970; Dochinger et al., 1970). In the experiments reported in these papers, ramets from chlorotic dwarf trees were injured more by simultaneous exposure to O_3 and SO_2 (both at 10 pphm) than the sum of injury to trees exposed to O_3 or SO_2 separately. The chlorotic dwarf disease is another manifestation of the high sensitivity of some eastern white pines to air pollution.

SYMPTOMATOLOGY OF THE WHITE PINE NEEDLE BLIGHTS

Differentiating the causes of the various needle blights of eastern white pine can be difficult. Faull (1922) stated that needle blight could be distinguished from SO_2 damage only on the current year needles. He observed that needle blight symptoms occurred only on needles emerging from the buds. In contrast, SO_2 damage occurred on older needles, although the current year needles were most sensitive.

Hepting and Berry (1961) and Linzon (1960, 1966, 1967 a,b) discussed the symptom differences that would aid in diagnosis of the specific causal agents.

Hepting and Berry (1961) discussed five common blight syndromes of eastern white pine. Two of the diseases were caused by fungi, Bifusella linearis and Scirrhia acicola, and were easily diagnosed by fruiting bodies. The other three, emergence tipburn (ET), post emergence chronic tipburn (PECT), and post emergence acute tipburn, were thought to be caused by air pollutants although proof at that time (1960) was lacking. Emergence tipburn symptoms, proven to be caused by O_3 (Berry, 1961; Berry and Ripperton, 1963), were distinguished from PECT in that only the current year needles were affected and there was a sharp line of demarcation between the injured and uninjured tissue. In PECT the symptoms could appear on older needles and there was a zone of chlorosis between the necrotic and healthy tissue. The cause of PECT was believed to be a chronic-type of SO_2 injury. Post emergence acute tipburn, thought to be associated with industrial pollutants (SO_2 or chlorine), also affected needles of all ages.

Linzon described the symptoms of a disease he called semimature-tissue needle blight (SNB). His studies included a description of the symptoms (Linzon, 1960) and histological examinations of injured tissues (Linzon 1962, 1966). The tissue most sensitive to SNB coincided with that part of the needle where suberization of the endodermis was occurring. Injury first appeared as faint, pinkish spots adjacent to stomata in the semimature tissue (Linzon, 1966).

In other studies, Linzon (1967a,b) attempted to distinguish between injury caused by O_3, SO_2, and SNB injury. The SNB-type injury seems to be the same as the ET reported by Berry and Hepting (1964). However, Linzon (1967b) did not believe that SNB and O_3 injury were the same. He fumigated SNB sensitive trees with high O_3 concentrations (40-60 pphm) and found them to be insensitive. If SNB is not caused by O_3, its cause remains unknown.

Because of the similarites between O_3 and SO_2 induced needle blights of eastern white pine it is difficult to determine the cause of a particular outbreak of disease on the basis of symptoms alone. At present, monitoring of pollutants is usually necessary to determine the cause of a particular outbreak of eastern white pine needle blight. Further complications arise when O_3-SO_2 interactions are considered.

Studies have been conducted to determine the feasibility of developing eastern white pine lines for use in a bioindicator system for the major air pollutants (Berry, 1964b, 1973, 1974). A reliable bioindicator system would lessen the requirements for expensive monitoring equipment.

IMPACT OF THE PHOTOCHEMICAL OXIDANTS ON FOREST VEGETATION

RESPONSE OF FOREST VEGETATION TO PAN

There has been only one major report in the literature that deals with the response of forest vegetation to peroxyacetyl nitrate (PAN). Drummond and Wood (1970) exposed 29 tree species to concentrations of PAN ranging between 10 and 20 pphm for 8 hr. They observed no injury on any of the species tested. However, Pearson et al. (1974) reported PAN-type injury on tomato in southwestern Ontario during 1972 and 1973. The potential for PAN damage to forest vegetation exists.

RESPONSE OF FOREST VEGETATION TO THE NITROGEN OXIDES

Van Haut and Stratman (1967) ranked 60 forest and shade tree species according to their sensitivity to short-term NO_2 exposures. Twenty-five of these species are presented in Table 3. The most sensitive species were Betula pendula, Malus sp., Pyrus sp., Larix decidua, and L. leptolepis. Nitrogen dioxide concentrations in the ambient air of the eastern United States rarely reach phytotoxic levels and when NO_2 concentrations are high, other pollutants are usually present. Resulting plant injury is therefore most commonly from pollutant combinations, rather than from exposure to NO_2 alone.

Nicholson (1977) studied the effect of NO_2 and O_3 singly and in combination on 12 clones of eastern white pine collected from ramets located near an industrial source of NO_2 and SO_2. He found that clonal sensitivity to the pollutant combination of O_3 + NO_2 or O_3 alone followed the field observations. NO_2 alone had little or no effect at the concentrations and exposure times used. Kress (1978c) used several levels of exposure to NO_2 alone and in combination but no injury was observed on loblolly pine when only NO_2 was used at concentrations up to 10 pphm for 6 hrs per day for 28 consecutive days.

RELATIVE SENSITIVITY OF THE SPECIES

Reports are available that list tree species according to their O_3 sensitivity (Dochinger, 1964; Davis and Gerhold, 1976). Table 4 presents a ranking of tree sensitivity to ozone and is reproduced from David and Gerhold (1976). The usefulness of relative sensitivity lists was discussed (Davis and Gerhold, 1976). They caution against placing a great dependence on relative sensitivity rankings. The plant material (source, age, etc), criteria for ranking (injury, growth), and the methods of study (exposure chamber, ambient air) may play an important role in the results of the experiments.

TABLE 3. SENSITIVITY OF TREE SPECIES TO NO_2*

Sensitive	Intermediate	Tolerant
	Broad leaved trees	
Betula pendula	Acer platinoides	Robinia pseudocacia
Malus sp.	Acer palmatum	Carpinus betulus
Pyrus sp.	Tilia cordata	Fagus silvatica
	Tilia platyphyllous	Sambucus nigra
		Ginko biloba
		Ulmus scabra
		Fagus silvatica atropurpurea
		Quercus robur
	Conifers	
Larix decidua	Picea pungens glauca	Taxus baccata
Larix leptolepis	Picea alba	Pinus austriaca
	Chamecyparis lawsoniana	Pinus montana nughus
	Abies homolepis	
	Abies pectinata	

* Taken from Van Haut and Stratman (1967).

The relative O_3 sensitivity of species in the following groups have been determined: conifers (Davis and Wood, 1972 - 18 species; Berry, 1971 - 3 species); deciduous trees (Davis and Wood, 1968 - 22 species; Wood and Davis, 1969; Wood, 1970 - 16 species; Wood and Coppolino, 1972 - 20 species); woody ornamentals (Davis and Coppolino, 1974; Wood and Coppolino, 1971), and woody shrubs and vines (Davis and Coppolino, 1976). In the reports mentioned above, species were classified as sensitive, intermediate or tolerant on the basis of their sensitivity to an 8-hr exposure to 25 pphm O_3.

Jensen (1973) determined the relative sensitivity of nine deciduous tree species on the basis of height growth during a five-month chronic O_3 fumigation (8 hrs daily for 5 days per week). The rank of only three of the nine species tested were in agreement with the rankings of Wood and Davis (1969). The ranking discrepancies between the two studies illustrate the problems encountered when attempting to compare results of studies using different plant material, methods, and criteria for ranking.

Trees found to be relatively sensitive to O_3 in separate studies include Fraxinus americana (Wilhour, 1970) and Populus tremuloides (Karnowsky, 1976).

TABLE 4. RELATIVE SUSCEPTIBILITY OF TREES TO OZONE*

Sensitive	Intermediate	Resistant
Ailanthus altissima	*Acer negundo*	*Abies balsamea*
Amelanchier alnifolia	*Cercis canadensis*	*Abies concolor*
Fraxinus americana	*Larix leptolepis*	*Acer grandidentatum*
Fraxinus pennsylvanica	*Libocedrus decurrens*	*Acer platanoides*
Gleditsia triacanthos	*Liquidambar styraciflua*	*Acer rubrum*
Juglans regia	*Pinus attneuata*	*Acer saccharum*
Larix decidua	*Pinus contorta*	*Betula pendula*
Liriodendron tulipifera	*Pinus echinata*	*Cornus florida*
Pinus banksiana	*Pinus elliotii*	*Fagus sylvatica*
Pinus coulteri	*Pinus lambertiana*	*Ilex opaca*
Pinus jeffreyi	*Pinus rigida*	*Juglans nigra*
Pinus nigra	*Pinus strobus*	*Juniperus occidentalis*
Pinus ponderosa	*Pinus sylvestris*	*Nyssa sylvatica*
Pinus radiata	*Pinus torreyana*	*Persea americana*
Pinus taeda	*Quercus coccinea*	*Picea abies*
Pinus virginiana	*Quercus palustris*	*Picea glauca*
Platanus occidentalis	*Quercus velutina*	*Picea pungens*
Populus maximowiczii X Trichocarpa	*Syringa vulgaris*	*Pinus resinosa*
Populus tremuloides	*Ulmus pavirfolia*	*Pinus sabiniana*
Quercus alba		*Pseudotsuga menziesii*
Quercus gambelii		*Pyrus communis*
Sorbus aucuparia		*Quercus imbricaria*
Syringa X chinensis		*Quercus macrocarpa*
		Quercus robur
		Quercus rubra
		Robinia pseudoacacia
		Sequoia sempervirens
		Sequoiadendron giganteum
		Thuja occidentalis
		Tilia americana
		Tilia cordata
		Tsuga canadensis

* Taken from Davis and Gerhold (1976).

Trees found to be relatively tolerant of O_3 in separate studies include Acer saccharum (Hibben, 1969a,b), Acer rubrum (Townsend and Dochinger, 1974), Quercus rubra and Cornus florida (Hibben, 1969b) and "Golden Delicious" apples (Kender and Spierings, 1975). Several Platanus species and Ulmus americana seedlings from several seed sources were slightly to moderately injured by exposure to 20 pphm O_3 for 3 hr (Santamour, 1969). Pinus nigra, P. densiflora and P. thunbergii were shown to be more sensitive to a pollution episode in New Jersey than other species such as Pinus strobus (Brennan and Davis, 1967).

Kohut and Krupa (1978) determined the sensitivity of several herbaceous plants of the north central U.S. forests. They listed a group of plants that are found native in the forests of the North Central region that were also sensitive to 8 and 15 pphm O_3 for only 4 hrs. These plants are also native to the forested areas of the north and southeastern portions of the United States. The sensitive plants listed were wild buckwheat (Polygonum convovulus), chicory (Cichonium intybus), daisy (Chrysanthemum leucanthemum), mustard (Brassica kaber) and ribes (Ribes sp.). Other work by Skelly (1977, unpublished) has identified O_3 typical symptoms on clematis (Clematis sp.) in the Shenandoah National Park of Virginia.

In studies of pollution damage to plants in New York City, Hibben (1969c) found oxidant-type injury on Pinus strobus, Syringa vulgaris, Ginko biloba, and several species of Ulmus. Wood (1971) found ozone-type stippling on American basswood, tree of heaven, a Prunus sp., Carolina silverbell, English oak, European mountain ash, flowering dogwood, grape, hawthorne, mulberry, and rhododendron in Philadelphia.

SENSITIVITY VARIATIONS WITHIN SPECIES

The intraspecific variations in sensitivity for many plants have led several researchers to propose breeding for air pollution tolerance as a measure to control air pollution damage to plants. Gerhold (1977) has reviewed the literature pertinent to the subject of forest tree breeding for air pollution resistance. Studies involving the differential resistance of woody plants to O_3 include Scotch pine (Gerhold and Palpant, 1968; Demeritt et al., 1971), American elm (Santamour, 1969; Karnowsky, 1974, Kress 1978b), English holly (Brennan and Leone, 1970), a hybrid poplar (Wood and Coppolino, 1972), eastern white pine (Houston and Stairs, 1972, 1973; Houston, 1974), trembling aspen (Karnowsky, 1976, 1977), azalea (Gesalman and Davis 1977), and loblolly pine (Kress, 1978a,b). In addition to uses in breeding for tolerance, the intraspecific variation in pollutant sensitivity may aid in developing a viable bioindicator system for detection of air pollutants (Berry, 1964, 1973; Kress and Skelly, 1977).

FACTORS AFFECTING SENSITIVITY TO O_3

Environmental factors that may affect the sensitivity of forest vegetation to O_3 have not been adequately studied. Heck (1968) provided a generalized review of the factors that affect the sensitivity of plants to air pollution.

In experiments with Virginia pine (Pinus virginiana) Davis and Wood (1973a,b) found that high relative humidity (85%), high pre- and post-exposure temperature (32 C), low exposure temperature (10 C), dark pre-exposure, and light post-exposure treatments favored injury from exposure to 25 pphm O_3 for 4 hr.

In similar experiments with white ash, Wilhour (1970) found that high pre-exposure, exposure and post-exposure relative humidity (80%) and high pre- and post-exposure temperature (27 C) and low exposure temperature (16 C) favored injury from exposure to 25 pphm O_3 for 4 hr. Fertilization increased the sensitivity of white ash seedlings. Fertilization of eastern white pine has been reported to alleviate air pollution damage (Spaulding and Hansbrough, 1943; Dochinger, 1964; Cotrufo and Berry, 1970; Cotrufo, 1974; Will and Skelly, 1974).

SORPTION OF AIR POLLUTANTS BY VEGETATION

There is evidence that vegetation is a major sink for air pollutants (Hill, 1971; Bennett and Hill, 1973). Differential rates of O_3 sorption by nine shade tree species and four seed sources of red maple were reported (Townsend, 1974). The rate of O_3 sorption was not necessarily related to the species sensitivity. Sorption by herbaceous plants has been shown to be greater than for selected trees (Thorne and Hanson, 1972).

GROWTH RESPONSE OF FOREST VEGETATION TO O_3

The growth responses of forest vegetation to air pollutant stresses have received little attention. Because of size restrictions of plants for use during pollutant exposure studies most of the available reports deal with seedlings.

Growth reductions of seedlings in response to O_3 exposures have been reported for American elm and Platanus species (Santamour, 1969) and eastern white pine (Feder and Perkins, 1977). Jensen (1973) found that height growth of sycamore, sugar maple, silver maple, black walnuts, green ash, and red maple was reduced by chronic exposure to 30 pphm O_3 (8 hr per day, 5 days per week for 6 months). The height growth of yellow poplar, white ash, and European black alder was not affected. Jensen and Dochinger (1974) found that chronic exposure of hybrid poplar cuttings to 15 pphm O_3 (8 hrs per day, 5 days per week, 6 weeks) caused reductions in height and dry weight. Acute exposure to 100 pphm O_3 for 2 hr caused extensive injury but no height or dry weight reduction.

Growth reductions may be due to the loss of leaf area available for photosynthesis (visible injury) or disruptions of metabolism that may include photosynthesis, respiration, or the patterns of photosynthate utilization. Botkin et al. (1971, 1972) found that exposure of branches of eastern white pine saplings to 50 pphm O_3 (or higher concentrations) for 4 hr caused suppression of net photosynthesis.

Barnes (1972a) found that chronic exposure of slash, pond, western, white and loblolly pine seedlings to 5 or 15 pphm O_3 usually caused depressed

rates of photosynthesis. The effect was more consistent with exposure to 15 pphm O_3. In addition, he found evidence of a photosynthesis stimulation after continuous exposure of slash, pond, and loblolly pine to 5 pphm O_3 for 36 days.

Barnes (1972b) found that chronic exposure of eastern white, shortleaf, slash; and pond pine seedlings to 5 pphm O_3 caused increases of soluble sugars and ascorbic acid. He postulated that these effects may represent an impairment of polysaccharide synthesis. Barnes and Berry (1969) discussed the relationship between carbohydrate and ascorbic acid levels and tipburn sensitivity of eastern white pine.

Wilkinson and Barnes (1973) found differences in the pattern of $^{14}CO_2$ fixation after exposure of eastern white and loblolly pine seedlings to 5 pphm O_3 for 10 minutes. The major effect of the O_3 exposures was to divert photosynthate from soluble sugars to other products.

RESPONSE OF FOREST VEGETATION TO POLLUTANT MIXTURES

The interaction of air pollutants in causing plant damage has received considerable attention in recent years. Reinert et al. (1975) reviewed the literature dealing with pollutant interactions. The interaction of O_3 and SO_2 in causing injury to tobacco was the first reported synergistic air pollutant interaction (Menser and Heggestad, 1966). Shortly thereafter Dochinger and co-workers determined that the chlorotic dwarf disease of eastern white pine was caused by the synergistic interaction of O_3 and SO_2 (Dochinger, 1968; Dochinger and Heck, 1969; Dochinger and Seliskar, 1970; Dochinger et al., 1970). Banfield (1972), Jaeger and Banfield (1970) and Houston (1974) reported greater-than-additive effects of O_3-SO_2 mixtures on eastern white pine. Costonis (1973) reported less-than-additive effects of O_3-SO_2 mixtures on eastern white pine. Greater-than-additive effects of O_3-SO_2 mixtures have also been observed on trembling aspen (Karnowsky, 1976) and 'Golden Delicious' apples (Kender and Spierings, 1975).

Kress (1972), Kohut (1972), and Kohut et al. (1976) studied the interaction of O_3 and PAN on hybrid poplar. Kress (1972), using sequential exposure, usually found greater-than-additive effects. Kohut (1972) and Kohut et al. (1976), using simultaneous exposures, found greater-than-additive, additive and less-than-additive effects in different replications of the same experiment.

Hill et al. (1974) reported an additive effect of SO_2 and NO_2 on selected native desert species and trembling aspen. Skelly et al. (1972) suggested that NO_2 in combination with SO_2 was causing injury to eastern white pine. The growth of eastern white pine (Stone and Skelly, 1974; Phillips et al., 1977a), loblolly pine (Phillips et al., 1977b), and yellow poplar (Stone and Skelly, 1974) near a NO_2-SO_2 source was reduced. Nicholson (1977) reported greater-than-additive injury effects on eastern white pine from O_3-NO_2 mixtures.

Kress and Skelly (1976, 1977) and Kress (1978 a,b,c,d) have provided the first reports of forest tree response to a three-pollutant interaction. They found that exposure of loblolly pine Pinus taeda L. and American sycamore Platanus occidentalis L. seedlings to combinations of O_3, SO_2, and NO_2 caused greater height growth reductions than exposure to any of the two pollutant combinations. The pollutant concentrations used in all the treatments were 14 pphm SO_2, 10 pphm NO_2, and 5 pphm O_3 and exposures lasted 6 hours per day for 28 consecutive days. In addition to visual injury, several height measurements were taken on both species in order to determine the effect of the pollutants on terminal growth. Significant growth reductions of 26% and 21% were observed in loblolly pines exposed to the O_3 + SO_2 and the SO_2 + NO_2 + O_3 treatments, respectively. When all three pollutants were combined, the resultant foliar injury was significantly different from that of the O_3 treatment, however, it was not significantly different from that of the O_3 + SO_2 treatment. Results using sycamore showed that foliar injury was not a reliable indicator of sensitivity under these experimental conditions since no treatment was consistently significantly different from any other. Treatment with all three pollutants produced a 45% and 25% growth reduction on sensitive and tolerant lines, respectively. This was especially important because no significant foliar symptoms were observed in either case. Significant growth reductions were also observed in the O_3 + SO_2 treatment where 34% and 17% growth reductions were observed on the sensitive and tolerant lines, respectively. Again, no significant foliar symptoms were observed.

COMMUNITY AND ECOSYSTEM EFFECTS

Several authors have outlined the potential effects of photochemical oxidant air pollutants on forest ecosystems. Miller (1973) and Miller and McBride (1975) described the results of the rather extensive San Bernardino Mountain studies in southern California. In that area the decline of ponderosa pine has led to undesirable changes in the plant community and forest ecosystem. Similar changes are possible if not already occurring in the eastern United States.

Treshow (1968) discussed the ways that air pollution could cause changes in plant populations and plant communities. The values of a baseline approach to air pollution research were outlined. Sinclair (1969) discussed air pollution as a selective force in forests. Not only will the pollutants select individuals and species through natural process, but selection of trees by man through tree breeding and planting will also affect the future composition of the forests.

Smith (1974) defined three classes of potential air pollution impacts on forests. In a Class I relationship the pollution load is low and vegetation will remain unaffected, and play a role as a sink for air pollutants. In a Class II relationship there may be subtle plant population and plant community changes caused by the predisposition of sensitive species to other abiotic stresses. Much of the eastern United States is probably in a Class II situation at the present time. In a Class III relationship the pollutant load is high and impacts on vegetation are obvious. At the present time, Class III situations are encountered only around industrial point sources of pollution.

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